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INTERLAMINAR FATIGUE CRACK GROWTH IN A THERMOPLASTIC-MATRIX FIBER COMPOSITE AT ROOM AND ELEVATED TEMPERATURES

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ABSTRACT

A study on the interlaminar fatigue crack growth behavior in a thermoplastic matrix composite at both room and elevated temperatures is presented. Experiments are conducted on an AS4-graphite fiber/polyamide J1 resin composite system. Details of interlaminar crack growth are studied, using double-cantilever beam (DCB) composite specimens under displacement-controlled cyclic loading. Governing fracture mechanics parameters, $(G_I)_{max}$, $(G_I)_{min}$ and ΔG_I during fatigue, are determined from a geometrically nonlinear analysis of the DCB experiment. The interlaminar fatigue experiments, conducted at room and at elevated temperatures up to the glass-transition temperature of the resin matrix, reveal that crack growth in the composite follows the Paris' type power-law equation at all test temperatures. The exponent n of the power-law expression remains relatively constant at temperatures below the glass-transition of the matrix resin. The value of n for the thermoplastic composite is significantly lower than those for thermoset-matrix composites and other thermoplastic composites such as AS4/PEEK. At a given temperature, the thermoplastic composite exhibits a distinct threshold ΔG_I in the interlaminar fatigue crack growth; the threshold ΔG_I is higher than those of typical thermoset composites. Unique characteristics of interlaminar fatigue crack growth and the effect of temperature on the crack growth rate are obtained. Delayed retardation of crack growth observed in monolithic metals and polymers due to variable loads is also studied in the AS4/J1 thermoplastic composite.

1. INTRODUCTION

Recent advances in fiber technology, polymer engineering and composite processing science have led to the development of a new class of thermoplastic-matrix fiber composites for advanced engineering applications, such as high-performance supersonic advanced aircraft structures [1-4]. Fatigue failure and damage tolerance of these advanced composite structures subjected cyclic loading in room and elevated temperature environments are of critical concern. Owing to the inherently low strength and high interlaminar stress along the interlaminar region in a fiber composite material, interlaminar cracks are commonly observed during manufacturing and service. Among various issues on damage and failure of the thermoplastic composites, interlaminar fatigue crack growth and fracture at various temperatures are problems of significant importance. In design, analysis, and life prediction of advance thermoplastic composite structures, interlaminar crack growth in the composites subjected to cyclic fatigue loading at elevated temperatures requires special attention due to its complexity and criticality.

While extensive research has been conducted on in-plane cyclic fatigue of thermoset composites such as graphite/epoxy systems, for example, Refs. [5-9], studies on the important issue of interlaminar fatigue of the thermoset composites have been limited [10-12]. For thermoplastic composites, only one paper is found on room-temperature interlaminar fatigue crack growth study [13] in the literature. An elevated-temperature interlaminar fatigue study on thermoplastic composite materials has not been available in the open literature to the authors' knowledge. Comparing with the in-plane fatigue problem of a thermoset fiber composite, mechanisms and micromechanics of interlaminar fatigue crack growth in an advanced, semicrystalline thermoplastic composite are generally more complex, owing to its resin matrix morphology, the microstructure at the fiber/matrix interface, and the involvement of transverse material properties and associated interlaminar deformation and stress. This situation is further complicated by the presence of an elevated temperature environment in which significant matrix ductility and microstructural/morphological changes can be developed in the interlaminar region. These are particularly true in a thermoplastic composite laminate subjected to cyclic compression, flexual and other out-of-plane loading modes in a high-temperature environment. Thus, to better evaluate the high-temperature thermoplastic composite long-term performance and to develop better life-prediction methodology for this class of new materials, clear understanding of basic interlaminar fatigue crack growth mechanisms and mechanics in the composite is obviously essential. In this paper, the fundamental behavior of interlaminar crack growth in a fiber-reinforced thermoplastic-matrix composite under opening-mode, cyclic fatigue loading is studied both at room and elevated temperature.

In the next section, an experimental program is presented, using an AS4/J1-polyamide composite double-cantilever-beam specimen (DCB) under opening-mode cyclic fatigue loading. Owing to the well-behaved self-similar growth of the interlaminar crack, a fracture mechanics approach is taken to determine quantitatively the relationship among the interlaminar crack growth rate, the loading level, and the crack and specimen geometry. The cyclic strain energy release rate is determined in Sec. 3 during fatigue crack growth by the use of a recently developed geometrically nonlinear fracture mechanics analysis [14]. Detailed results are given in Section 4. Several unique characteristics and basic mechanisms of the cyclic interlaminar crack growth in the AS4/J1 composite are discussed. A power-law relationship of Paris' type is obtained for the interlaminar crack growth in the composite at all temperature levels studied. The influence of variable-load interactions on the interlaminar fatigue crack rate and the associated delayed retardation behavior is studied. Also, the effect of temperature on the rate of crack growth and the threshold level of crack propagation are addressed. Several conclusions drawn from the results obtained are given in Sec. 5.

2. INTERLAMINAR FATIGUE CRACK GROWTH EXPERIMENTS AT ROOM AND ELEVATED TEMPERATURES

2.1 Material

The material system used in the experiment was made from continuous graphite fibers (Hercules AS4) and a semicrystalline thermoplastic model matrix resin (Du Pont J1-polyamide), referred to in this paper as the AS4/J1 composite. The composite was provided by Du Pont in a compression-molded laminate form of unidirectional layup. The laminates were prepared from unidirectional prepreg tapes made by a melt-impregnation process. A matched-mold molding process was then employed. The process was carried out at 300°C under 1000 psi in a 6x6 inch steel mold. After solidification, the mold was cooled down to room temperature under pressure.

The neat resin (i.e., the J1 polymer) had a low density (1.04 g.cm^3) and a relatively high T_g (145°C dry-as-mold, 105°C at 100% R.H.). It was soluble in formic acid but insensitive to most other organic solvents. The J1 polymer had a low melt viscosity and could be processed at a relatively low temperature. The constitutive thermal and mechanical properties of the J1 neat resin and the AS4/J1 composite at various temperatures have been studied extensively and reported in [15-17].

2.2 Specimen Preparation

Double cantilever beam (DCB) specimens with the fiber direction parallel to the longer side, L, as shown in Fig. 1, were machined from the composite panel. All specimens had a length of 6 inches, a width of 0.75 inches, and a nominal thickness of 0.2 inches. To properly introduce an initial interlaminar crack to the specimen, a single-layer Teflon-coated cloth of 1.5 inch wide and 0.02 inch thick was placed at the mid-plane of each composite plate during fabrication. Before tests, specimens were soaked in liquid nitrogen, and the machined initial notch was extended to approximately 2 inches along the mid-plane by an end-wedge loading.

To determine the interlaminar crack growth length accurately during cyclic fatigue, all specimens were coated on their side surfaces with a white correction fluid. A graded scale was attached to each specimen along the expected crack extension path to allow precise measurements of the crack length. The interlaminar fatigue crack propagation in the AS4/J1 composite was carefully monitored with a long-range, high-magnification telemicroscope through the window of a high-temperature environmental chamber.

2.3 Experimental Procedure

All experiments were conducted in a servohydraulic test system, as shown in Fig. 2(a). The composite specimen was pin-loaded in the grips as shown in Fig. 2(b). The cyclic fatigue loading was introduced in a displacement-controlled mode at a frequency of 1Hz. The minimum-to-maximum-displacement ratio was kept at 0.1 in the study (Fig. 3), i.e., $R' = \delta_{min}/\delta_{max} = 0.1$. Several test temperatures were selected to cover the range from the ambient room temperature up to the glass-transition temperature, $T_g = 145°C$, of the J1 neat resin. An MTS Model 651.11B high-temperature environmental chamber was used to control the temperature. The chamber was a microprocessor-controlled unit to ensure the accuracy of the temperature. Measurements were taken in the beginning of the test and at preselected intervals as the test progressed. Each experiment lasted approximately a week to reach the threshold region where the fatigue crack growth became negligibly small.

3. DETERMINATION OF STRAIN ENERGY RELEASE RATE DURING CYCLIC INTERLAMINAR FATIGUE CRACK GROWTH

To evaluate quantitatively the fundamental nature of interlaminar fatigue crack growth in the thermoplastic-matrix composite, proper parameters need to be established accurately to describe the driving force for the subcritical crack growth and the material resistance to the interlaminar crack growth. The self-similar nature of the interlaminar crack growth observed in the cyclic fatigue experiment, as will be discussed in the next Section, warrants the consideration of the problem in the context of composite fracture mechanics [18]. Thus, the local driving force for subcritical interlaminar crack growth may be expressed in terms of the strain energy release rate, G_I, and the amplitude of the energy release rate during fatigue crack growth, $\Delta G_I = (G_I)_{max} - (G_I)_{min}$. The material resistance to the interlaminar crack growth, i.e., the interlaminar fracture toughness, is taken as the critical strain energy release rate G_{Ic}. Various analytical and experimental methods have been introduced to determine the values of G_I, ΔG_I and G_{Ic}. For example, the area method [19], the compliance method [20], and several nonlinear methods [14,21] are commonly used to study the interlaminar crack growth in composites. In this study, the geometrically nonlinear analysis of the DCB composite specimen recently developed by Wang and Suemasu [14], was used to determine the G_I and ΔG_I values during cyclic fatigue. The large deformation observed in the DCB fatigue crack growth experiment, especially at elevated temperatures, is taken into consideration. In the present nonlinear deformation theory, both large rotational and translational displacements of the loading arm (Fig. 1) contribute significantly to the final solution. Details of the derivation are very tedious and can be found in Ref. [14].

The analytical solution for the interlaminar strain energy release rate G_I in a DCB composite specimen can be expressed in a rather complicated series form [14] as:

$$G_I = -\frac{2}{b}\left[\frac{\partial U}{\partial a}\right]_{\delta = \text{constant}}$$

$$= \frac{4E_{11}I}{3a^2b}\{q_1^2[1 - 6\alpha q_1 + (27\alpha^2 - \frac{8}{35})q_1^2 + \alpha(\frac{199}{35} - 96\alpha^2)q_1^3$$

$$+ (120\alpha^4 - \frac{9}{70}\alpha^2 + \frac{9088}{40425})q_1^4] - q_1(a\frac{dq_1}{da})[2 - 9\alpha q_1 + (36\alpha^2 - \frac{32}{35})q_1^2$$

$$+ \alpha(\frac{199}{14} - 120\alpha^2)q_1^3 + (144\alpha^4 - \frac{9}{35}\alpha^2 + \frac{18176}{13475})q_1^4] + \ldots\} \qquad (1)$$

where

$$a\frac{dq_1}{da} = -\frac{3}{2}\left(\frac{\delta}{a}\right) - \frac{243}{16}\alpha\left(\frac{\delta}{a}\right)^2 - (\frac{81}{35} + \frac{4455}{64}\alpha^2)\left(\frac{\delta}{\alpha}\right)^3$$

$$-\left(\frac{161595}{1024}\alpha^2 + \frac{3483}{256}\right)\alpha\left(\frac{\delta}{\alpha}\right)^4 + \left(\frac{1379395}{4096}\alpha^4 + \frac{952803}{5120}\alpha^2 - \frac{1296}{2695}\right)\left(\frac{\delta}{a}\right)^5 + \ldots \qquad (2)$$

$$q_1 = \frac{3}{2}\left(\frac{\delta}{a}\right) + \frac{81}{16}\alpha\left(\frac{\delta}{a}\right)^2 + \left(\frac{27}{35} + \frac{891}{64}\alpha^2\right)\left(\frac{\delta}{a}\right)^3 + \alpha\left(\frac{23085}{1024}\alpha^2 + \frac{3483}{1280}\right)\left(\frac{\delta}{a}\right)^4$$

$$-\left(\frac{142155}{4096}\alpha^2 + \frac{952803}{35840}\alpha^4 - \frac{1296}{13475}\right)\left(\frac{\delta}{a}\right)^5 + \ldots \qquad (3)$$

$$\alpha = \frac{(d + h/2)}{a} \qquad (4)$$

and

U = strain energy in one arm of the DCB specimen,

a = interlaminar crack length,

b = specimen width.

δ = load-line displacement,

E_{11} = elastic modulus of the composite in fiber direction,

I = moment of inertia of the cracked cross section,

$2h$ = specimen thickness.

We remark that the above equation is developed for very large deflection of the DCB composite specimen for the interlaminar G_{Ic} determination. In the present fatigue study, subcritical interlaminar crack growth is examined in the test specimen with approximately 1/2 to 1/3 of the deflection encountered in a static interlaminar crack growth experiment. Therefore, taking only the fundamental mode of deformation and using the same analytical scheme discussed in [14], one can obtain a simple, convenient expression for the G_I during the interlaminar fatigue crack growth as

$$G_I = \frac{9E_{11}I}{a^4 b}\,\delta^2\left[1 + \frac{15}{4}\alpha\left(\frac{\delta}{a}\right) - \left(\frac{189}{64}\alpha^2 + \frac{6}{7}\right)\left(\frac{\delta}{a}\right)^2\right] \tag{5}$$

A detailed study on the accuracy and convergence of the solution has been reported in Ref. [22].

4. RESULTS AND DISCUSSION

The fundamental nature of interlaminar crack growth in the thermoplastic composite under cyclic fatigue is examined by a combined experimental and analytical approach described in Sec. 2 and 3. Experiments were conducted on the AS4/J1 composite DCB specimens at four different temperatures, i.e., 25°, 100°, 120°, and 145°C. In the experiments, δ_{max} and δ_{min} were changed but the ratio $R' = \delta_{min}/\delta_{max}$ was kept constant with $R' = 0.1$. The values of δ_{max} used were 0.115, 0.15, 0.2 and 0.25 inch. In each experiment, the interlaminar crack growth in the composite was examined and recorded during the entire fatigue history. Owing to the nature of the displacement-controlled fatigue experiment and the continuous change in the nominal stress during the interlaminar crack growth, the ratio R of the local crack-tip driving forces, $R = [(G_I)_{min}/(G_I)_{max}]^{1/2}$, is used as a parameter in studying the interlaminar fatigue crack problem. Subsequent analyses were carried out to evaluate the corresponding driving forces $(G_I)_{max}$ and $(G_I)_{min}$, and the associated energy release rate amplitude, ΔG_I. Note that $R = [(G_I)_{min}/(G_I)_{max}]^{1/2}$ is equivalent to the conventional R in a small deflection case. Variation of $[(G_I)_{min}/(G_I)_{max}]^{1/2}$ as a function of the fatigue cycles during the cyclic interlaminar crack growth at various temperatures is shown in Fig. 4. Clearly, the mean-stress R parameter remains relatively constant in all of the fatigue crack growth experiments at different temperatures. (Also, an accompanying interlaminar crack growth experiment under a monotonically increasing load was conducted to provide the reference information for evaluating the cyclic fatigue crack growth behavior. For example, the change in strain energy release rate during interlaminar crack growth in the AS4/J1 composite under a monotonically increasing load at 100°C is shown in Fig. 5 for illustration.) The detailed analysis of interlaminar fatigue crack growth rate, the effect of temperature on fatigue crack propagation, and the delayed retardation of subcritical crack growth due to variable-load interactions are given in this section.

4.1 Characteristics of Interlaminar Fatigue Crack Growth

General characteristics of interlaminar crack growth under cyclic loading were examined at various stages during fatigue. The macroscopic crack was observed to propagate in a self-similar manner through the interlaminar region (Fig. 6). No crack branching or deflection was observed in any of the experiments conducted. The self-similar growth of an interlaminar crack under cyclic fatigue occurred at all four temperatures studied. Crack-tip fiber bridging was observed, perhaps due to local fiber misalignment, at both room and elevated temperatures [Figs. 7(a) & 7(b)].

The macroscopic interlaminar fatigue crack growth was generally well behaved, as shown in Fig. 8. As anticipated, the cyclic interlaminar crack growth depends upon the initial crack length and the local crack tip driving force ΔG_I during fatigue. The change in cyclic strain energy release rate ΔG_I during the interlaminar crack growth was determined at various fatigue cycles. For illustration, in Fig. 9, variation of ΔG_I versus N is shown for the case of $\delta_{max} = 0.15$ and $R' = 0.1$ at $T = 100°C$. A monotonic decrease in ΔG_I is observed during the entire fatigue crack growth history. We remark that for the convenience of later analysis, the interlaminar fatigue crack growth data were approximated by smooth curves through a least-square curve fitting method. An incremental polynomial method [23] was used to determine the rate of the interlaminar fatigue crack growth, da/dN.

4.2 Interlaminar Crack Growth Rate During Fatigue

The interlaminar fatigue crack growth behavior is generally examined in terms of the crack growth rate da/dN and the amplitude of the associated crack-tip driving force ΔG_I during the cyclic loading history. A detailed analysis of da/dN vs. ΔG_I for each experiment was conducted. Typical results of the interlaminar crack growth rate versus cyclic strain energy release rate are shown in Fig. 10 for the cases of $\delta_{max} = 0.15$ and 0.2 inch, with $R' = 0.1$ and $T = 100°C$. The results exhibit a well behaved sigmodal shape. Both the threshold region where crack growth becomes negligible and the rapid crack growth instability region are clearly observable. In the intermediate range of ΔG_I, a power-law relationship of Paris' type [24] in the following form can be clearly determined:

$$da/dN = B\,(\Delta G_I)^n \tag{6}$$

where the coefficient B and the exponent n are dependent upon matrix ductility, fiber volume fraction, composite microstructure, the environmental condition and the state of stress [25]. Although at a given temperature, slight variation in the value of n is observed in experiments with different test variables, the values of n obtained here are very consistent. For example, in the case of AS4/J1 composite subjected to δ_{max} = 0.15 inch and R' = 0.1 at 100°C, the value of n is approximately 3.71. The thermoplastic composite also exhibits a distinct threshold ΔG_I for the interlaminar crack growth. The threshold ΔG_I is higher than those observed for typical thermoset composites.

We remark that this n value is significantly lower than those reported for thermoset-matrix composites [11,12] and for other thermoplastic-matrix composites such as an AS4/PEEK system [13]. It is also significantly lower than the value reported for the interlaminar fatigue crack growth in a SMC short-fiber composite [22]. However, the n value is appreciably higher than those obtained for monolithic ductile polymers and metals [26,27]. The unique characteristics clearly demonstrate the significant effect of matrix ductility on cyclic subcritical interlaminar crack growth in the composite. Effects of fiber constraints and the microscopic stress state on embrittlement of the ductile matrix during the interlaminar crack growth need to be studied from a micromechanical point of view [28]. The local matrix ductility apparently plays a very significant role in governing the interlaminar crack growth behavior in the thermoplastic-matrix composite. Thus, many of the fatigue damage and failure problems associated with cyclic crack growth in ductile polymers and metals are also expected to appear in the interlaminar fatigue crack growth and fracture problems of thermoplastic composite materials.

4.3 Effect of Temperature

It is well-known that temperature has significant effects on thermal and mechanical properties of a polymer-matrix composite. In a thermoplastic composite with a semicrystalline matrix phase, the effect of temperature on local deformation and subcritical crack growth is expected to be even more pronounced, owing to the temperature-dependent crystalline matrix morphology [29-31]. In the absence of a complete micromechanics theory to account for the complex nature of the heterogeneous microstructure, a macroscopic mechanics approximation of the fatigue crack growth is taken in this study as a first-order approach. At a temperature below the glass transition temperature of the neat J1 resin, the matrix phase in the composite remains glassy and thermoelastic; thus, the change in the interlaminar strain energy release rate, ΔG_I, may be evaluated accurately in accordance with Eq. 4 during cyclic interlaminar fatigue crack growth.

Crack growth rates during the interlaminar fatigue of the AS4/J1 composite are obtained at various temperatures and shown in Figs. 10-13. All of the results follow the power law type relationship with ΔG_I. It is interesting to note that the exponent n in the power-law interlaminar fatigue crack growth expression for the thermoplastic composite does not seem to be affected by the temperature below 120°C (Fig. 14), whereas the coefficient B changes with temperature. The insensitivity of the value of n to temperature may result from the fact that below the glass transition temperature, the resin matrix remains in a consistently glassy state of a similar nature in its mechanical properties. Consequently, the matrix-dominated interlaminar crack growth rate is dictated by the local ΔG_I during the mechanical fatigue and not affected by the thermal activation process at these temperatures. Near and above the glass transition temperature, one has to include the time and temperature dependent inelastic contributions to the crack growth and in the evaluation of ΔG_I, which will be addressed in a separate report.

4.4 Variable-Load Interaction Effect - Delayed Retardation in Interlaminar Fatigue Crack Growth

During cyclic fatigue of a ductile material, it is well known [27] that variable-load interaction effects lead to the so-called delayed retardation of fatigue crack propagation. That is, load fluctuations or variable loading patterns during cyclic fatigue result in crack growth rate deceleration after the overload and resumption of normal growth rate after the crack moves through the overload plastic zone. A similar situation is expected for the interlaminar crack growth in the semi-crystalline thermoplastic composite with a ductile matrix under variable-amplitude nominal loads, such as the current displacement-controlled cyclic loading in the DCB specimen. This situation is of particular importance for the thermoplastic composite at elevated temperatures at which a large amount of inelastic deformation occurs. Thus the delayed retardation of the interlaminar fatigue crack growth in the AS4/J1 composite is examined in this study.

As indicated in previous studies [17, 32], the AS4/J1 composite possesses a significant amount of ductility, both in the in-plane transverse and interlaminar directions, even at room temperature. For example, the significantly nonlinear behavior of the interlaminar normal stress-strain relationship of the AS4/J1 thermoplastic composite at different temperatures is shown in Fig. 15. The crack growth during interlaminar fatigue of the DCB composite under the displacement-controlled cyclic loading experiences a high local crack-tip driving force G_I at the early short-crack stage and a low G_I as the crack growth proceeds at a later stage, as shown in Fig. 16. The higher load excursion at the early crack growth stage during fatigue introduces larger inelastic crack-tip deformation and damage. Thus, once the crack grows through the high-load inelastic zone, resumption of normal crack growth rate is expected at a later stage. In Fig. 17 the interlaminar fatigue crack growth rate behavior through the high-load affected region reveals the deceleration with a minimum growth rate after the crack propagates part way through the affected region. It is clear that in the initial fatigue crack growth stage, the interlaminar crack growth rate da/dN is attenuated, and as the crack grows further through the initial large plastic zone, the crack growth rate gradually recovers its nominal rate. The dimension of the high-load affected region is approximately 0.025 inch in the AS4/J1 composite DCB specimen and its size may be affected by temperature and loading rate.

5. CONCLUSIONS

Based on the experimental and analytical results obtained in this study, the following conclusions may be reached:

(1.) The interlaminar crack growth in a AS4/J1 polyamide thermoplastic composite under opening-mode cyclic fatigue is well behaved. The cyclic fatigue crack growth at all temperatures studied is in a self-similar manner. Thus, the use of proper fracture mechanics experiments and analyses enables one to obtain quantitative information of the interlaminar fatigue crack growth problem.

(2.) Owing to the large deformations occurred in the thermoplastic composite DCB specimen under loading, especially at high temperatures, the geometrically nonlinear effect in the test needs to be included in proper evaluation of the change in cyclic strain energy release rate during the interlaminar fatigue crack growth.

(3.) Interlaminar fatigue crack growth rates in the AS4/J1 thermoplastic composite at all temperatures studied under opening-mode cyclic loading are found to follow a power-law relationship of Paris' type, $da/dN = B(\Delta G_I)^n$, with the driving force expressed in terms of the amptitude of cyclic strain energy release rate ΔG_I during crack growth.

(4.) The exponent, n, in the power-law interlaminar crack growth rate expression for the AS4/J1 composite is found to be much lower than those for thermoset composite systems, other thermoplastic composites such as AS4/PEEK, and short-fiber SMC composites but higher than those obtained for monolithic metals and polymers. This is apparently attributed to the matrix ductility of the semi-crystalline polyamide resin in the thermoplastic composite.

(5.) Experiments conducted at room temperature and at elevated temperatures give a relatively constant value of n for the cases with $T < (T_g - 20°C)$. In the interlaminar fatigue crack growth experiment, if the temperature is near or greater than T_g, the value of n decreases dramatically with increasing T and time-temperature-dependent inelastic and damage effects need to be included.

(6.) The influence of mean stress on interlaminar fatigue crack growth may be studied by using the parameter $R = [(G_I)_{min} / (G_I)_{max}]^{1/2}$. In the displacement-controlled AS4/J1 composite DCB specimen under fatigue, the value R remains relative constant during the interlaminar fatigue crack growth in the composite at all temperatures studied.

(7.) Owing to the ductile nature of the semi-crystalline matrix phase in the thermoplastic composite, the variable load-interaction effect is expected and delayed retardation of interlaminar fatigue crack growth is observed in the AS4/J1 thermoplastic composite system at all temperatures.

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8. LIST OF FIGURE CAPTIONS

Fig. 1 Double-cantilever-beam (DCB) Specimen for Studying Interlaminar Fatigue Crack Growth in AS4/J1 Thermoplastic Composite.

Fig. 2 Experiment Facilities and Setup for Studying Interlaminar Fatigue Crack Growth in Thermoplastic Composite at Elevated-Temperatures; (a) Overall View of Test Setup, and (b) DCB Composite Specimen in High-Temperature Environmental Chamber.

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Fig. 17 Delayed Retardation of Interlaminar Fatigue Crack Growth in AS4/J1 Thermoplastic Composite DCB Specimen under Cyclic Loading.

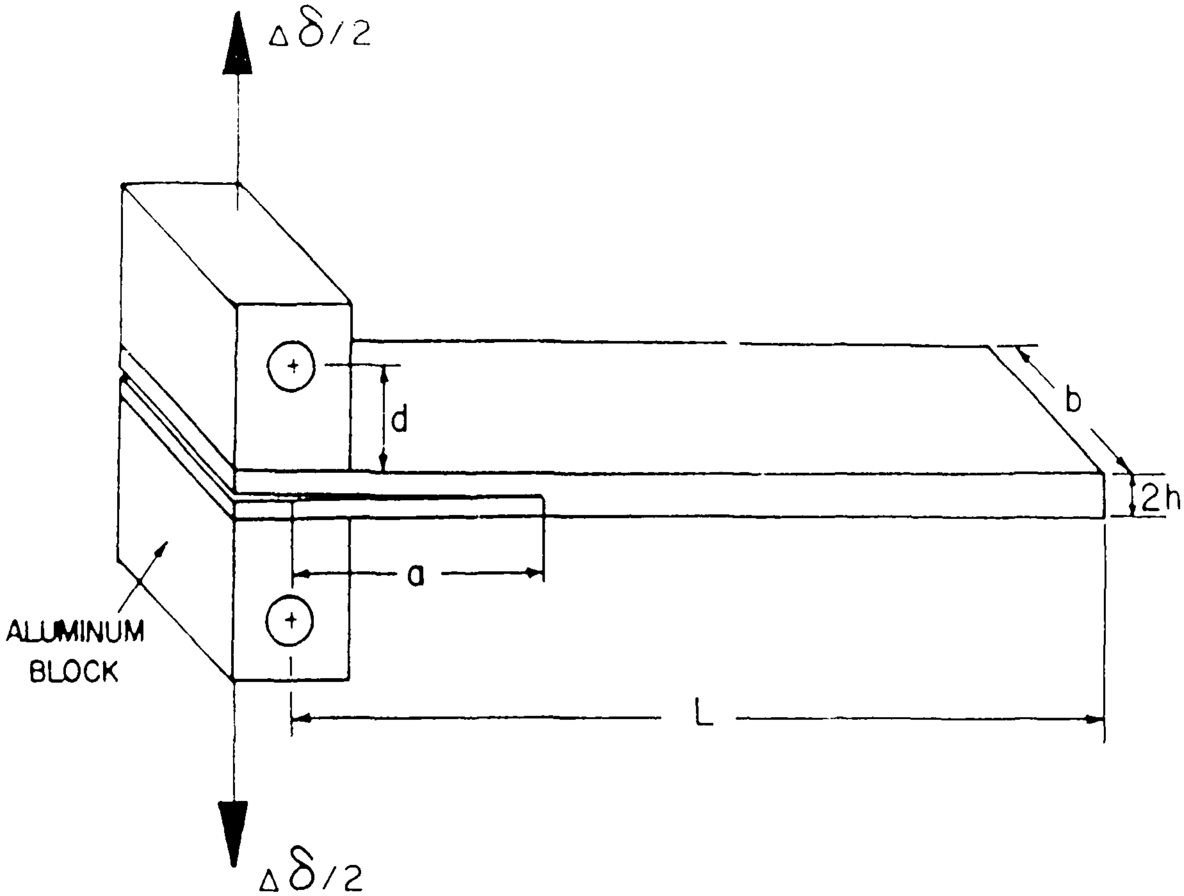
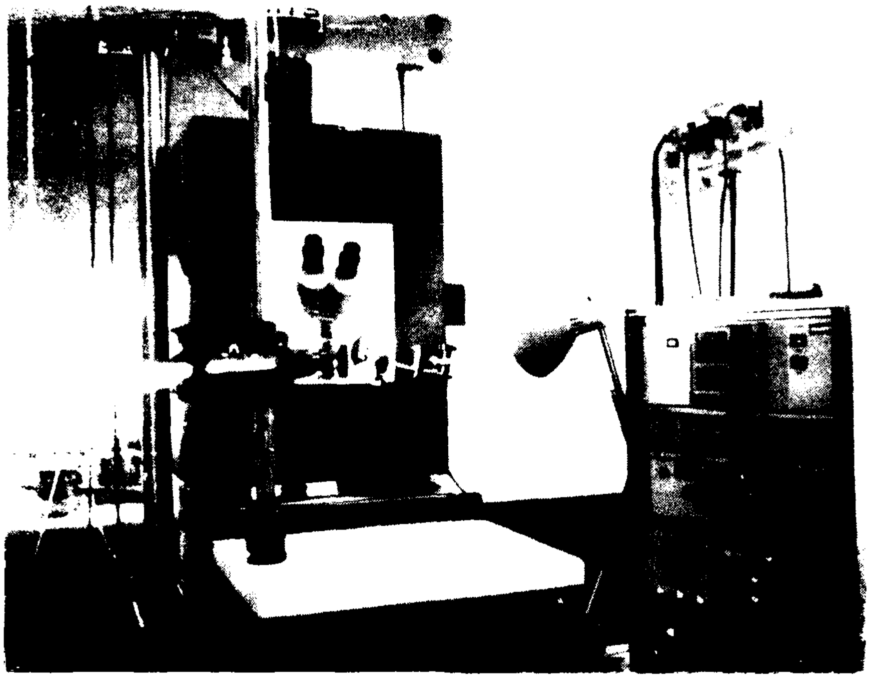
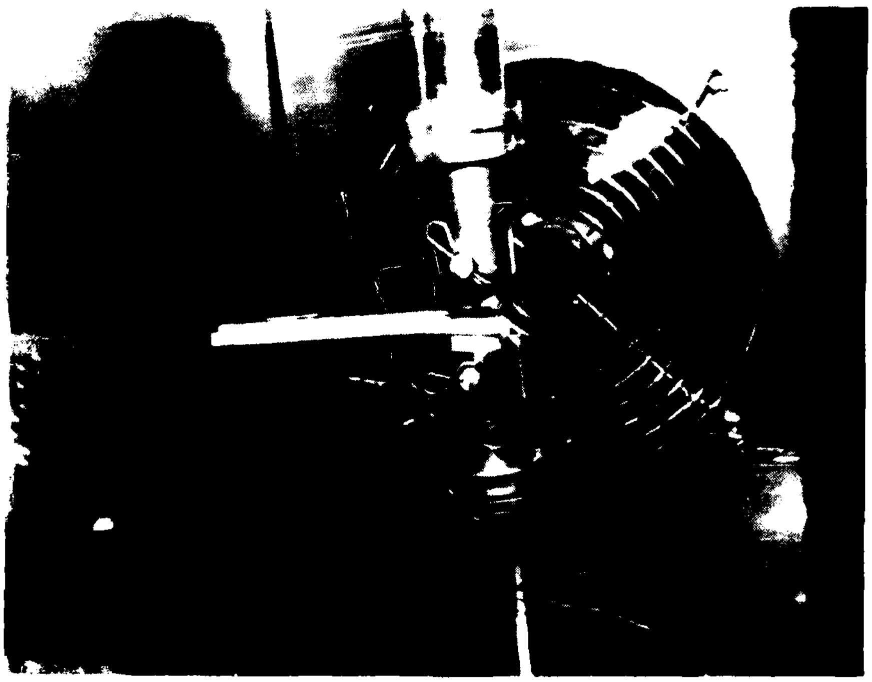


Fig. 1 Double cantilever-beam (DCB) Specimen for Studying Interlaminar Fatigue Crack Growth in AS4/J1 Thermoplastic Composite.

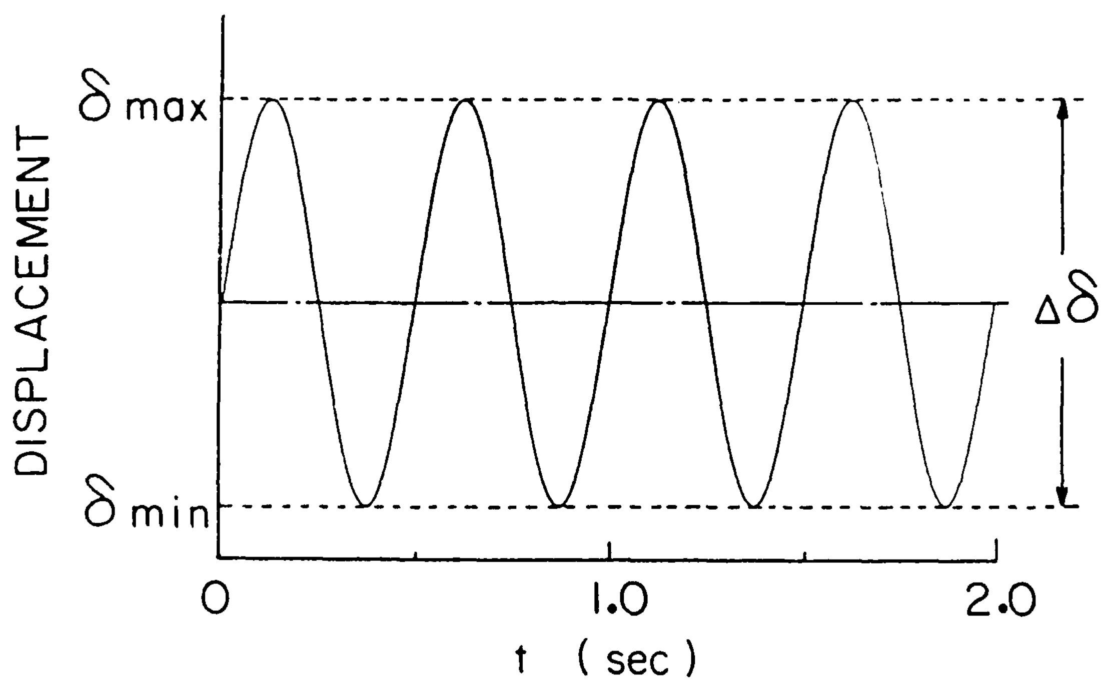


2(a)



2(b)

Fig. 2 Experimental Facilities and Setup for Studying Interlaminar Fatigue Crack Growth in Thermoplastic Composite at Elevated Temperatures: (a) Overall View of Test Setup, and (b) DCB Composite Specimen in High Temperature Environmental Chamber.



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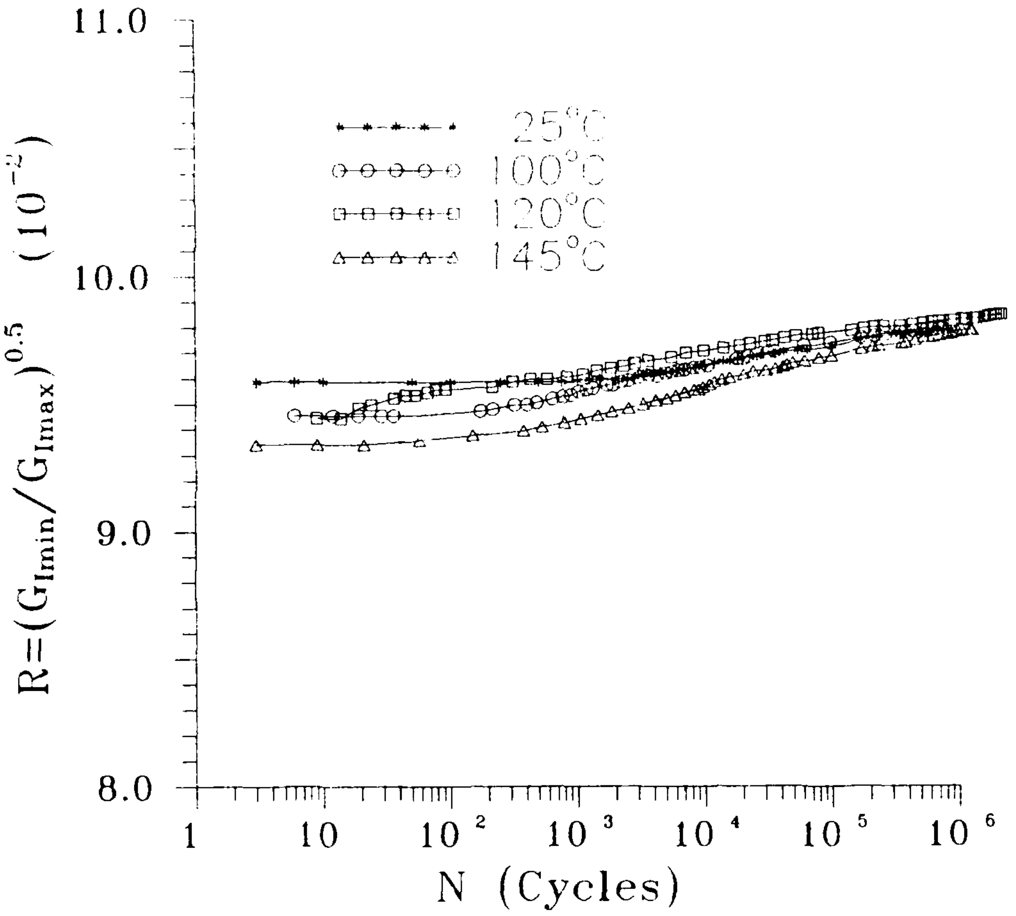

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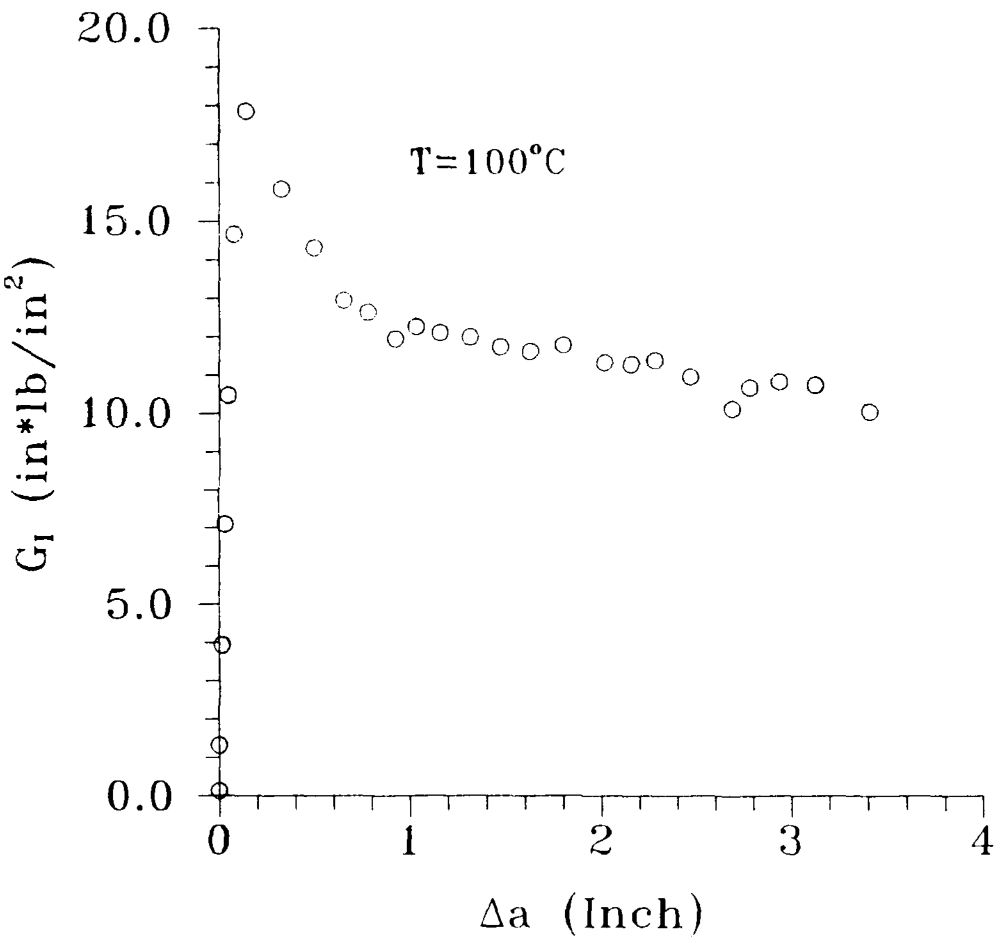


Fig. 5 Change in *Strain Energy Release Rate during Interlaminar* Crack Growth in AS4/J1 Polyamide Composite under Monotonically Increasing Load at T = 100°C.

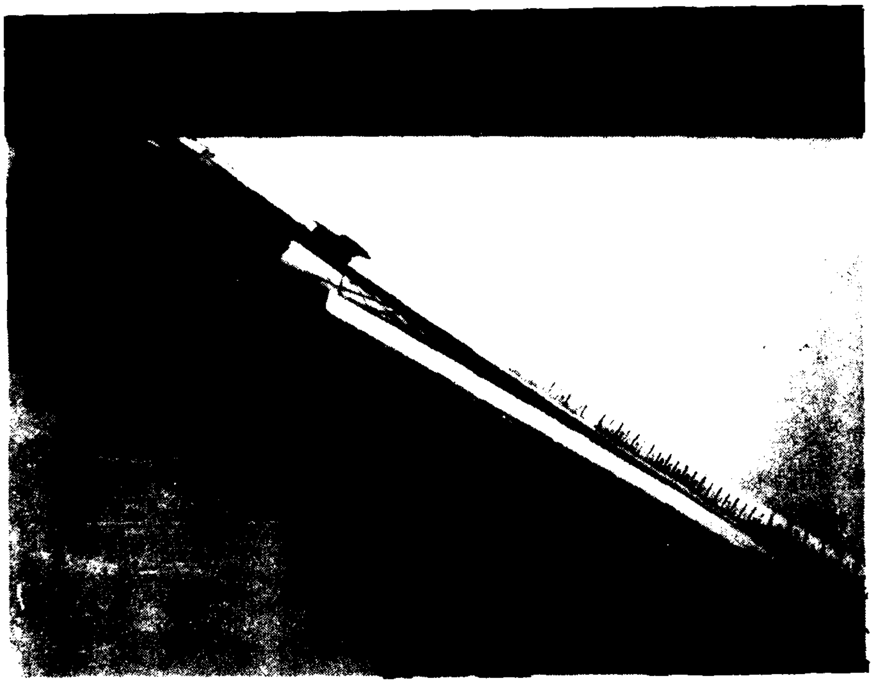
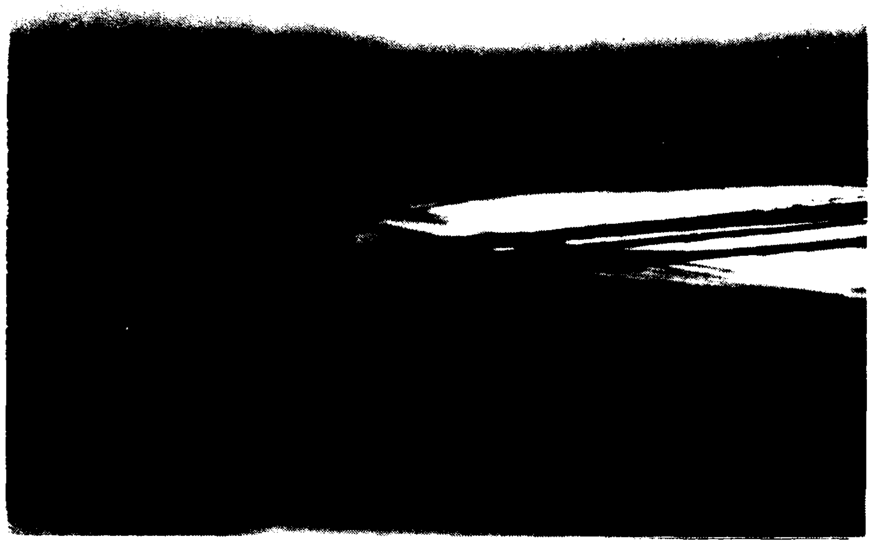
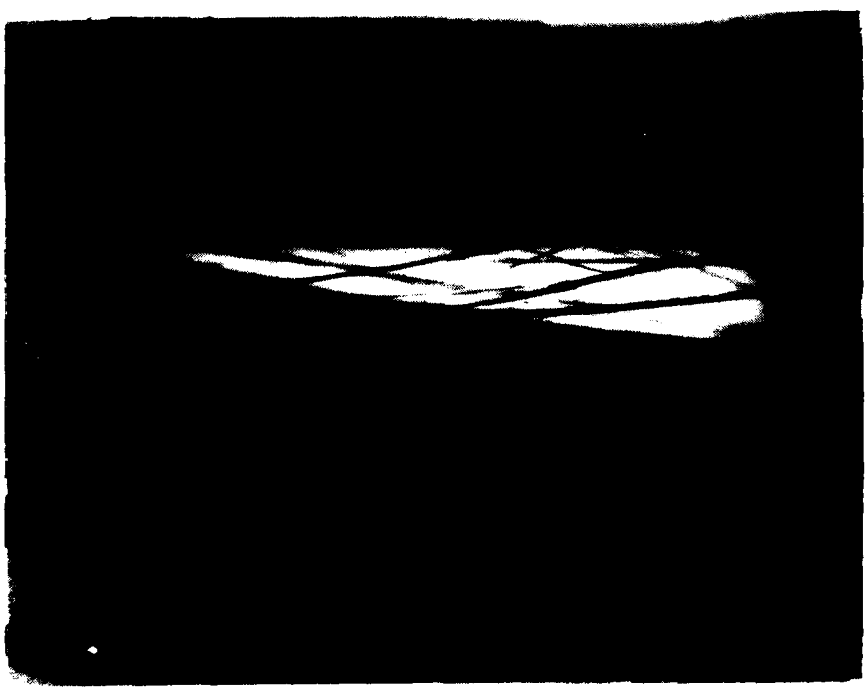


Fig. 6 Self-Similar Growth of Interlaminar Crack in AS4/J1 Polyamide Thermoplastic Composite under Cyclic Fatigue Loading at $T = 100°C$.

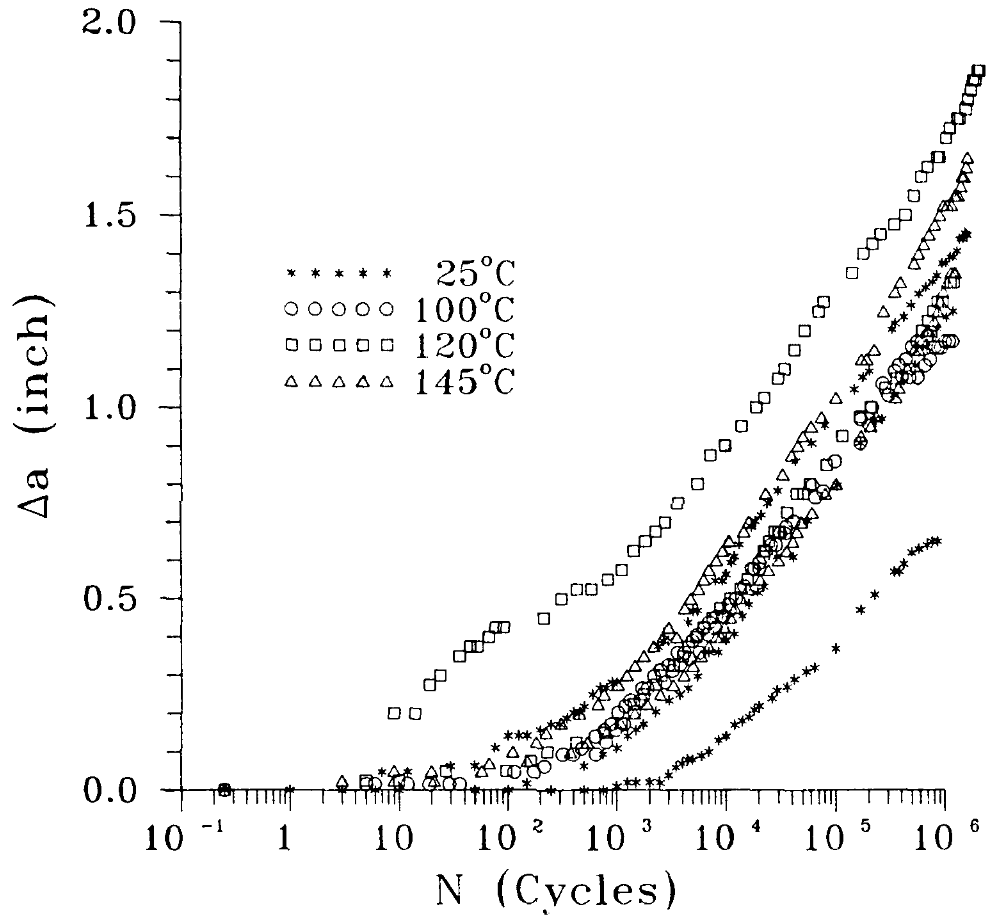


7(a)



7(b)

Fig. 7 Crack-Tip Fiber Bridging during Interlaminar Crack Growth in AS4/J1 Polyamide Composite under Fatigue Loading; (a) T = 25°C, (b) T = 120°C.



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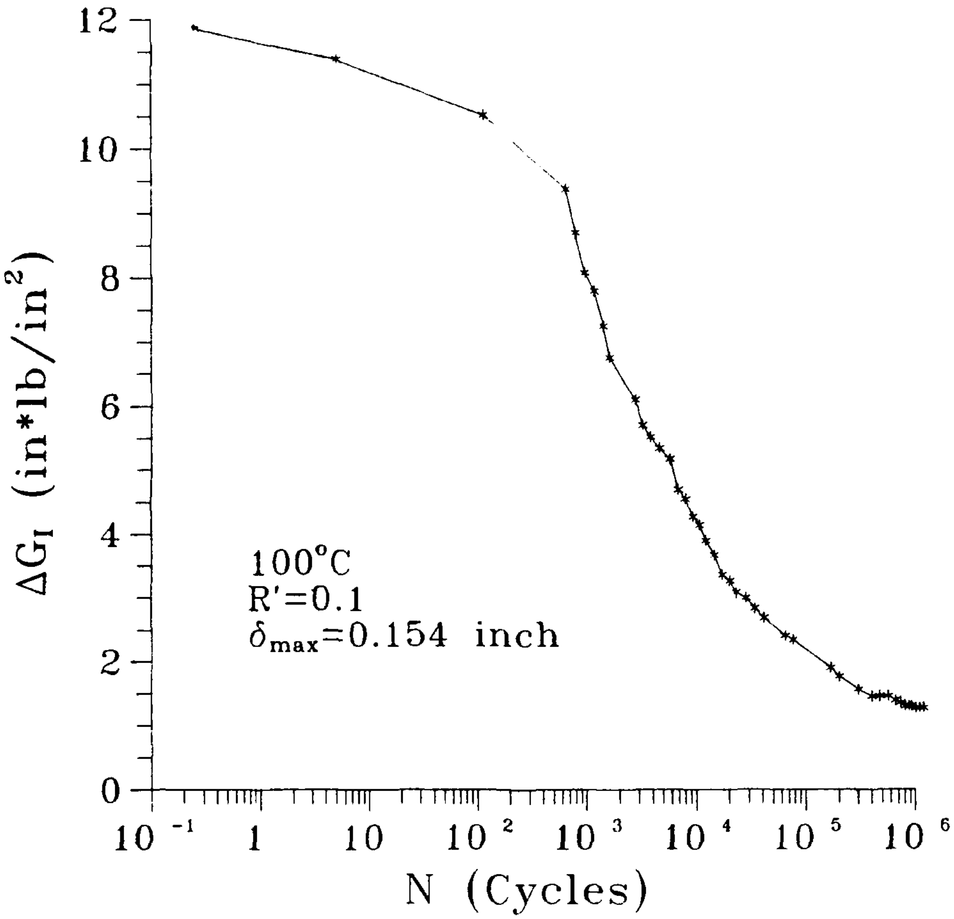

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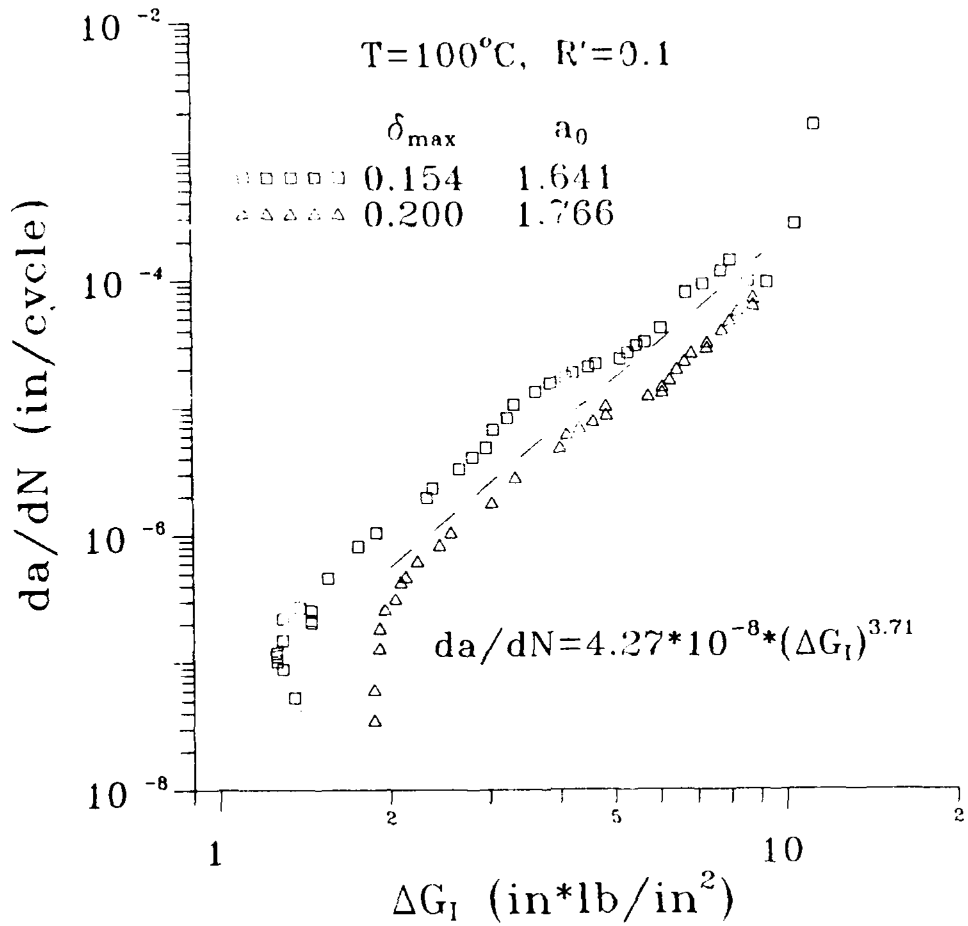


Fig. 10 Interlaminar Crack Growth Rate da/dN vs. ΔG_I in AS4/J1 Thermoplastic Composite under Cyclic Fatigue at T = 100°C.

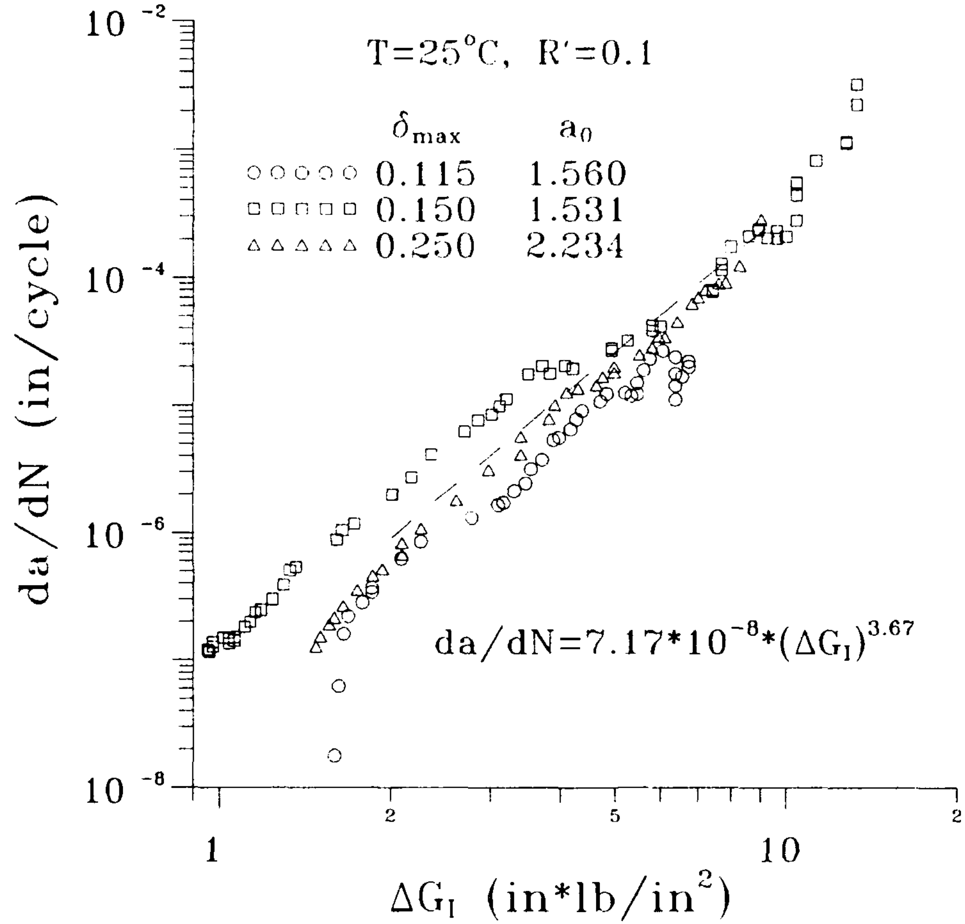


Fig. 11 Interlaminar Crack Growth Rate da/dN vs. ΔG_I in AS4/J1 Thermoplastic Composite under Cyclic Fatigue at T = 25°C.

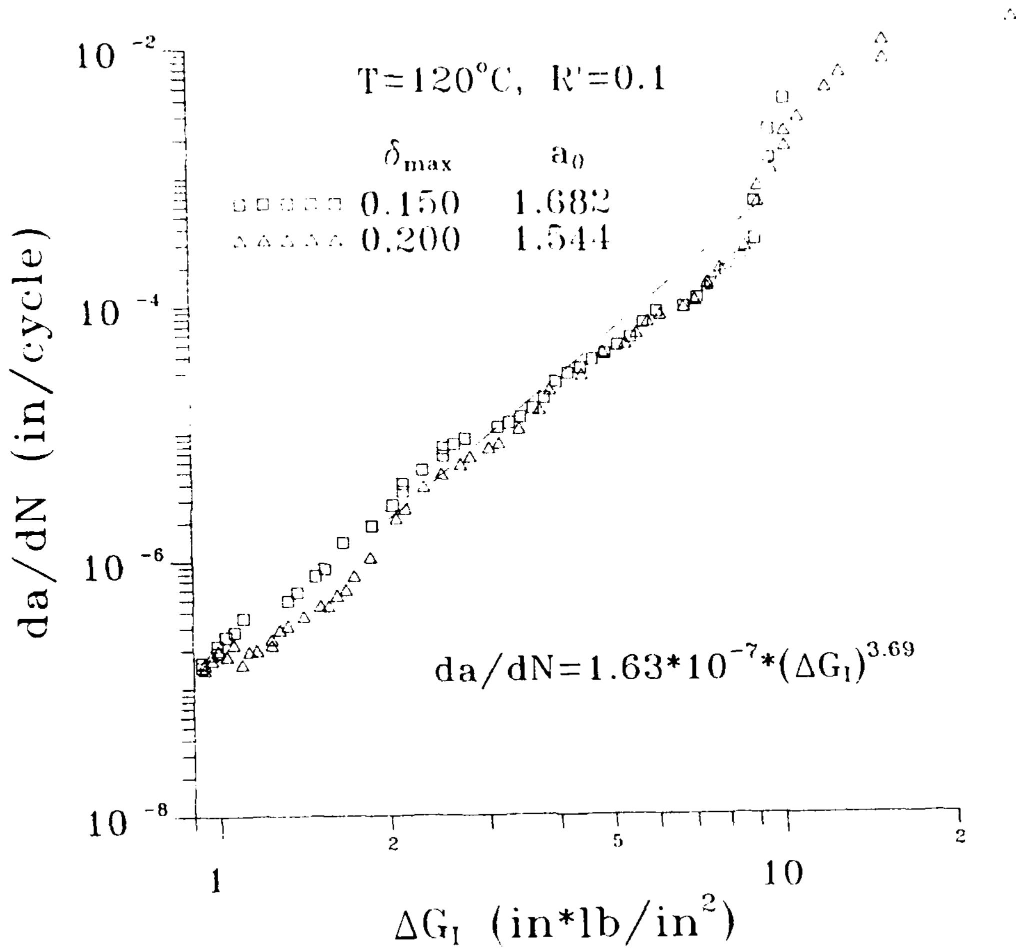


Fig. 12 Interlaminar Crack Growth Rate da/dN vs. ΔG_I in AS4/J1 Thermoplastic Composite under Cyclic Fatigue at T = 120°C.

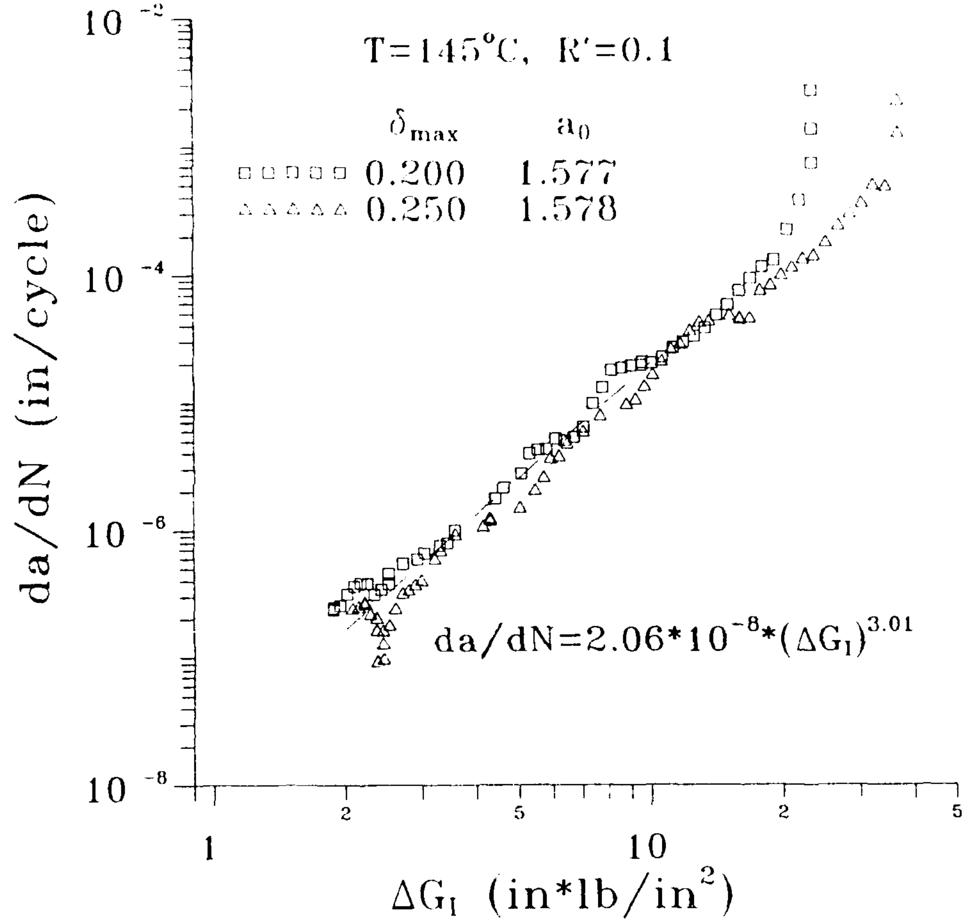


Fig. 13 Interlaminar Crack Growth Rate da/dN vs. ΔG_I in AS4/J1 Thermoplastic Composite under Cyclic Fatigue at T = 145°C.

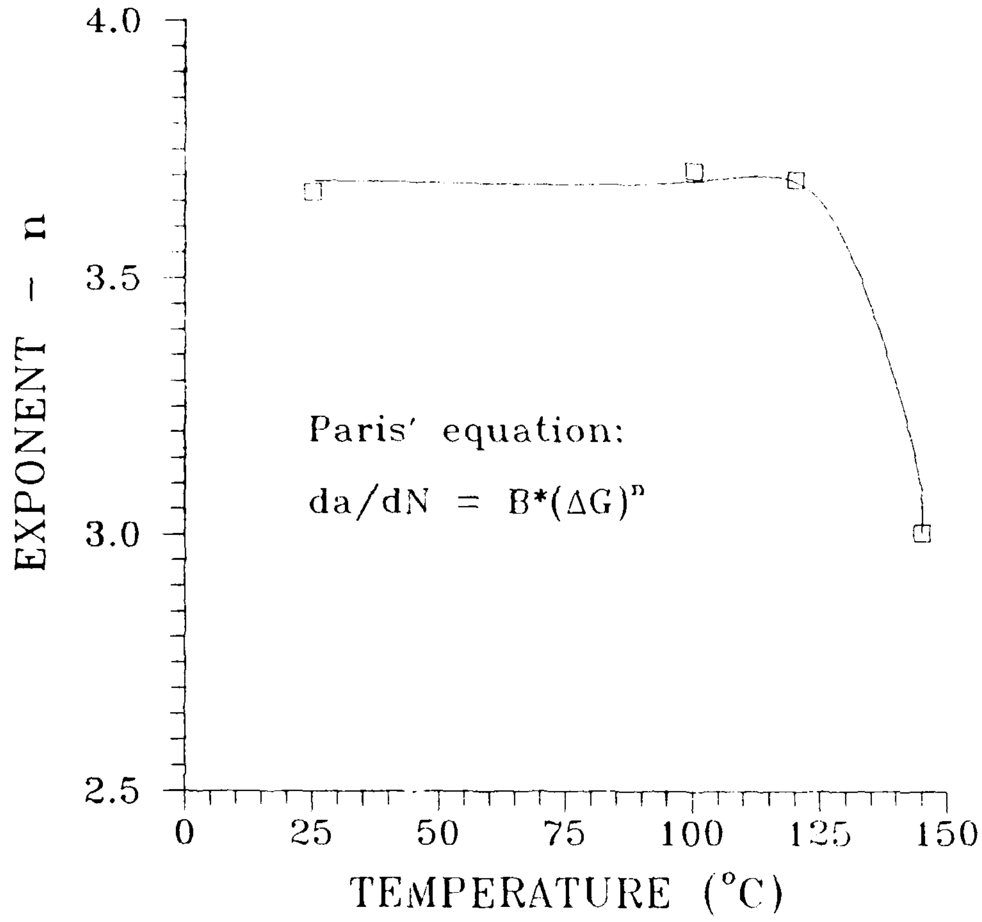
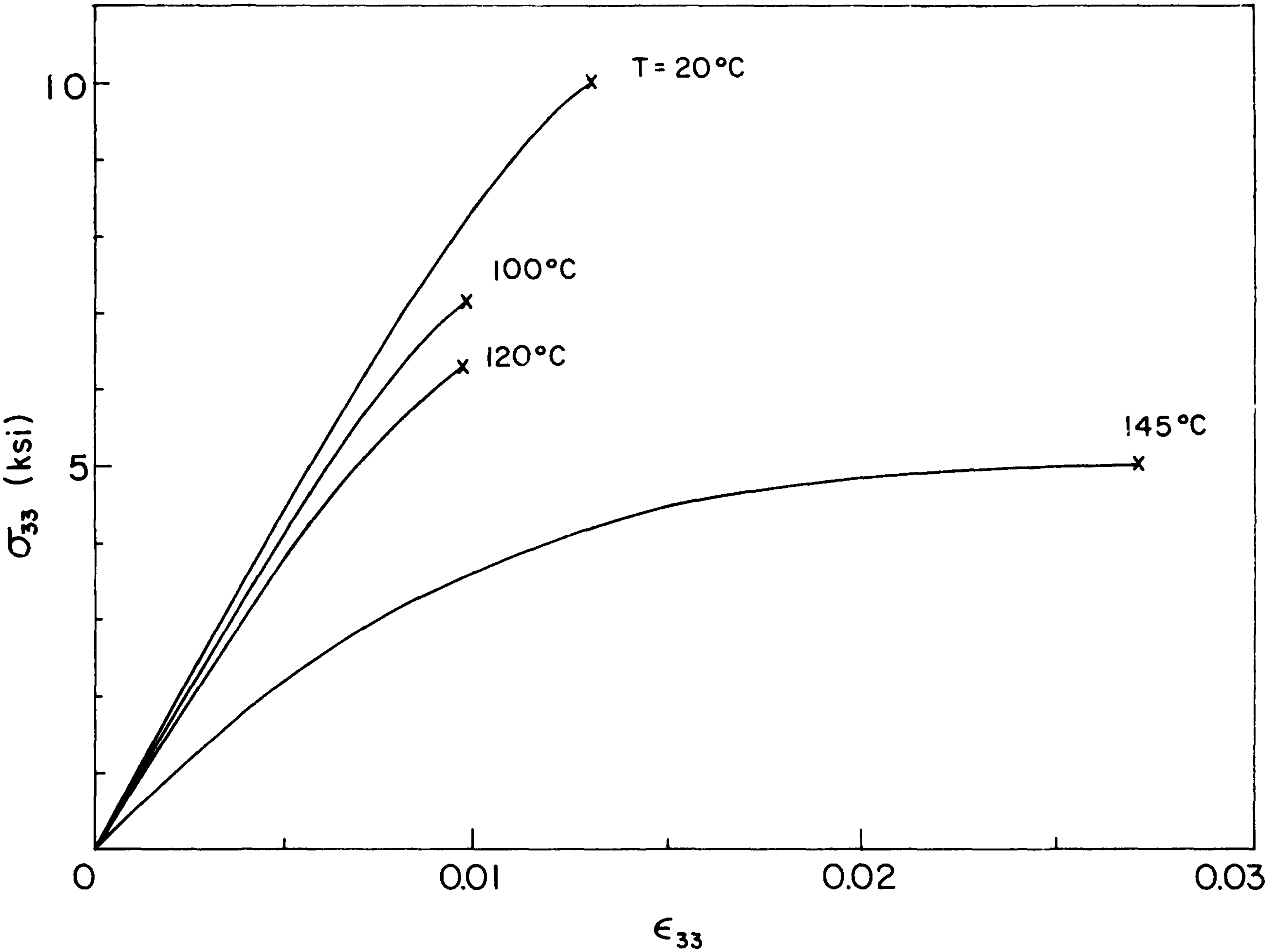


Fig. 14 Effect of Temperature *T* on Exponent *n* in Power-Law Interlaminar Crack Growth Equation for AS4/J1 Thermoplastic Composite during Cyclic Fatigue.



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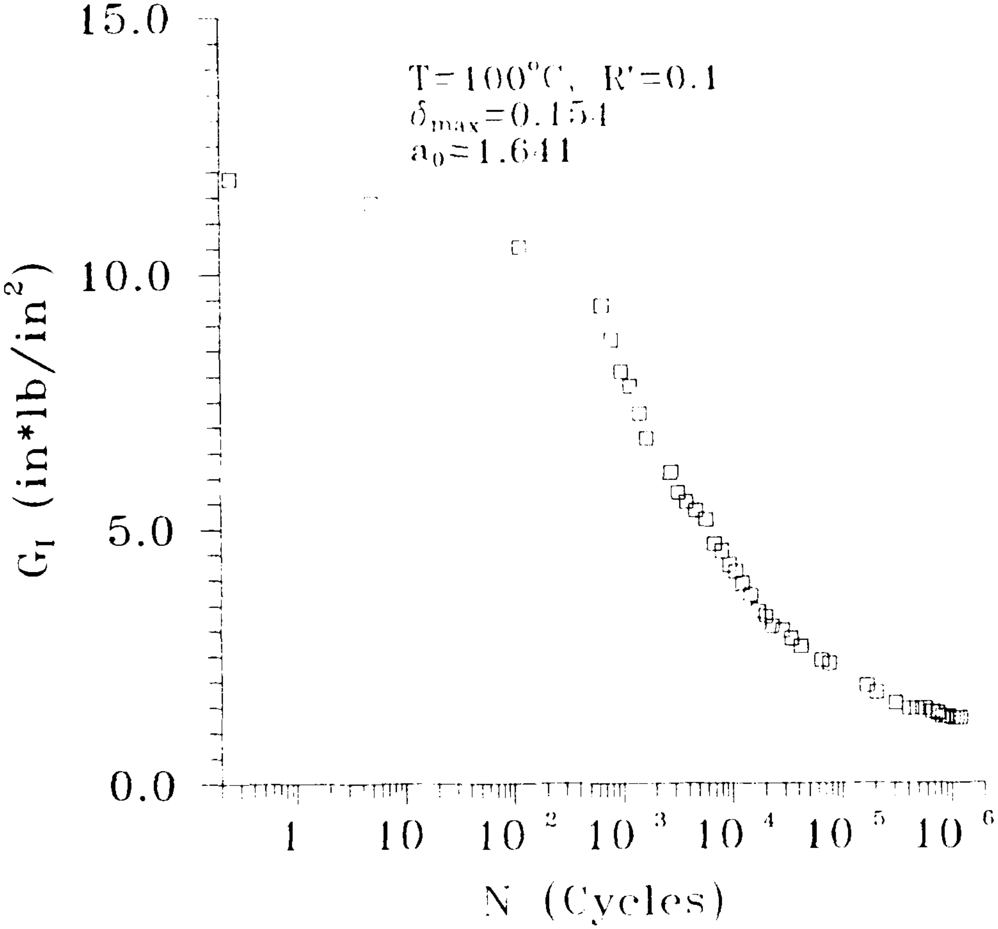

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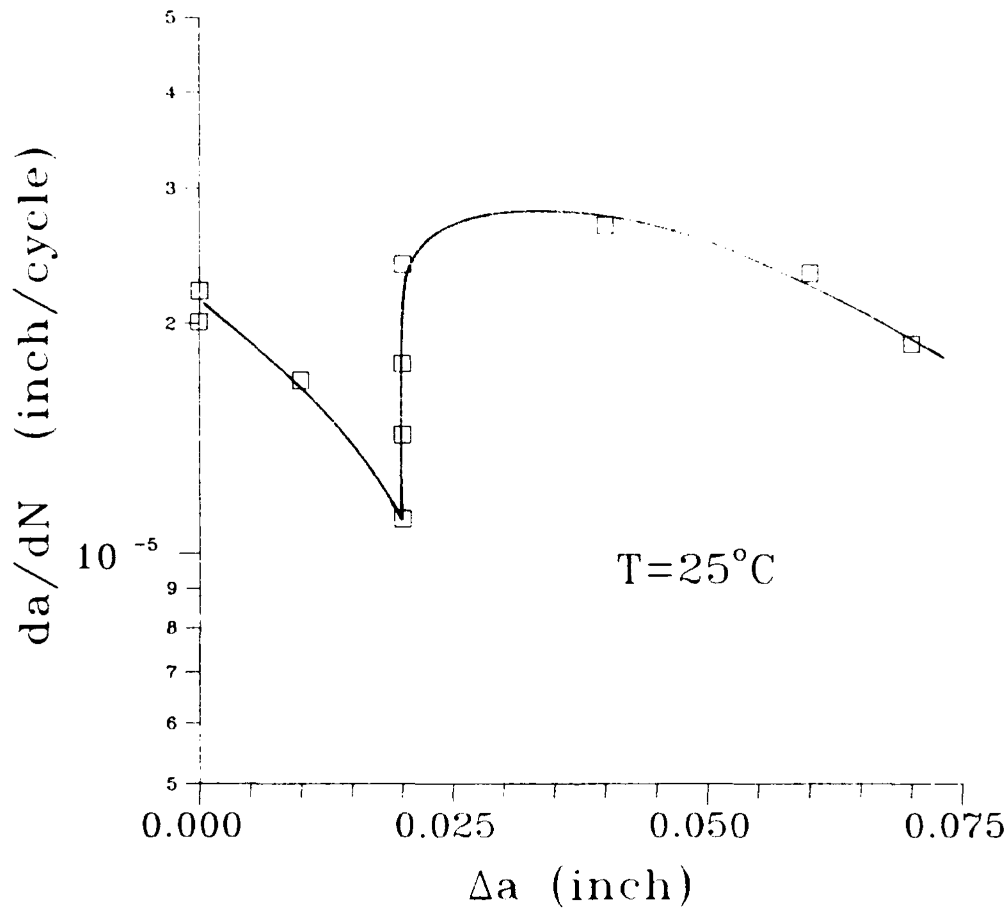

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